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Spectral and spatial characterisation of laser-driven positron beams

G Sarri[1], J Warwick[1], W Schumaker[2], K Poder[3], J Cole[3], D Doria[1], T Dzelzainis[1], K Krushelnick[4], S Kuschel[5], S P D Mangles[3], Z Najmudin[3], L Romagnani[6], G M Samarin[1], D Symes[7], A G R Thomas[8], M Yeung[1] and M Zepf[1,5]

[1] School of Mathematics and Physics, Queen's University Belfast, University Road, Belfast BT7 1NN, UK
[2] SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
[3] The John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, London SW72BZ, UK
[4] Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 481099-2099, USA
[5] Helmholtz Institute Jena, Frobelstieg 3, 07743 Jena, Germany
[6] LULI, Ecole Polytechnique, CNRS, CEA, UPMC, 91128 Palaiseau, France
[7] Central Laser facility, Rutherford Appleton Laboratory, Didcot, Oxfordshire OX11 0QX, UK
[8] Lancaster University, Lancaster LA1 4YB, UK

E-mail: g.sarri@qub.ac.uk

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Abstract

The generation of high-quality relativistic positron beams is a central area of research in experimental physics, due to their potential relevance in a wide range of scientific and engineering areas, ranging from fundamental science to practical applications. There is now growing interest in developing hybrid machines that will combine plasma-based acceleration techniques with more conventional radio-frequency accelerators, in order to minimise the size and cost of these machines. Here we report on recent experiments on laser-driven generation of high-quality positron beams using a relatively low energy and potentially table-top laser system. The results obtained indicate that current technology allows to create, in a compact setup, positron beams suitable for injection in radio-frequency accelerators.

Keywords: laser wakefield acceleration, positron beams, injection, hybrid accelerators

(Some figures may appear in colour only in the online journal)

1. Introduction

The generation of high-quality positron beams is a central area of research in experimental physics, due to their direct application in a wide range of physical subjects, including nuclear physics, particle physics, astrophysics, and material science. Arguably, the simplest way of generating positrons relies on the electromagnetic cascade initiated by an ultra-relativistic beam (mainly of electrons or photons) as it propagates through a high-Z solid target. In its simplest form, the cascade comprises two fundamental steps: 1. generation of a high-energy photon following bremsstrahlung of the electron (positron) in the field of a nucleus [1], and 2. generation of an electron–positron pair during the interaction of such photon with the field of the nucleus [2]. Higher order phenomena might also take place, mostly depending on the ratio between the thickness of the target and the radiation length of the material used [3]. As a rule of thumb, one can approximate each step of the cascade to occur within one radiation length of the material that, in the ultra-relativistic approximation, can be expressed as [4]:

$$L_{\mathrm{RAD}} \approx \frac{1}{4\alpha(Z\alpha)^2 n \lambda_{\mathrm{C}} L_0} \tag{1}$$

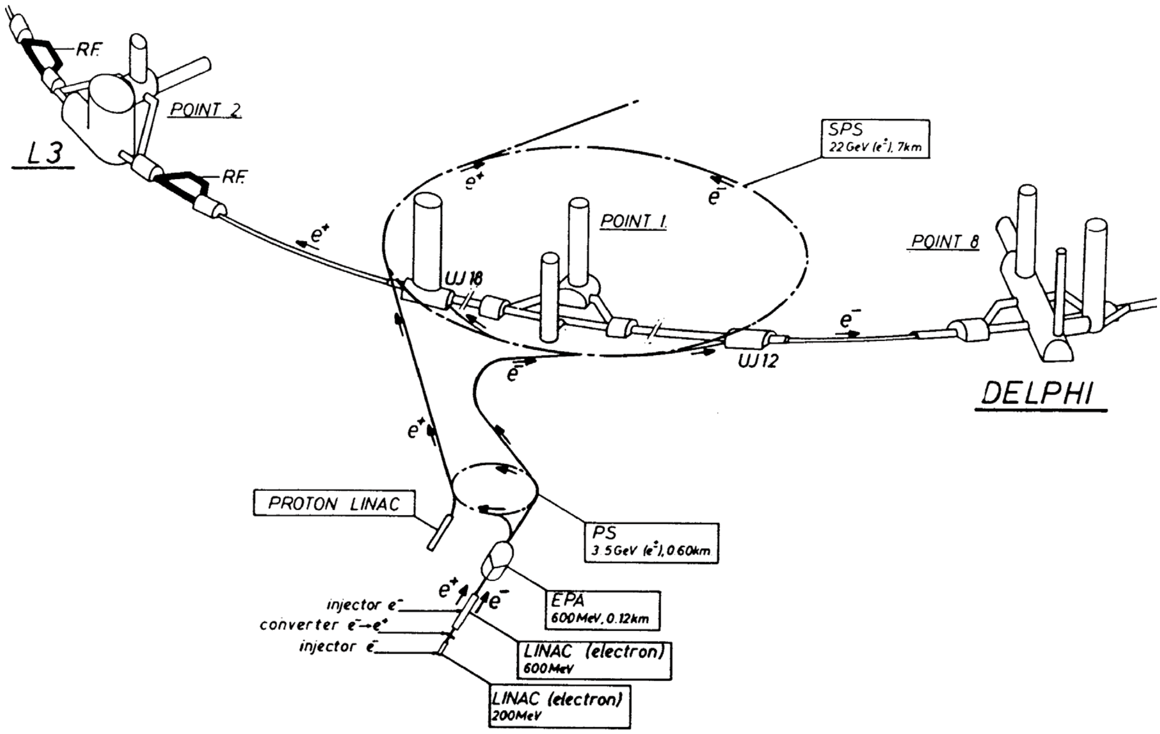

Figure 1. Sketch of the LEP, the electron–positron collider at CERN, up to the super proton synchrotron (SPS) (from [8]).

with α being the fine structure constant, Z the atomic number and n the atom number density in the material, λ_C the Compton wavelength, and $L_0 = \log(183Z^{-1/3}) - f(Z\alpha)$, with $f(x) = \sum_{\xi=1}^{\infty} x^2/\xi(x^2 + \xi^2)$. This length is usually of the order of a few mm for the most common high-Z materials (for example, 4.1 mm for tantalum and 5.6 mm for lead). Due to the nature of the cascade, the resulting positron beam presents a broad divergence and a broad spectrum, the latter being well approximated by a Maxwell–Jüttner distribution [5]. It is thus necessary to store and post-accelerate positrons generated with such mechanism, if collimated and mono-energetic positron beams are required. This is the traditional way positron beams are generated in conventional electron–positron colliders. As an example, the highest center of mass electron–positron collider ever built was the LEP in CERN (decommissioned in 2001 to give room to the large hadron collider, LHC). A sketch of the operation of LEP is given in figure 1.

In this machine, a 0.22 GeV electron beam was generated by accelerating an electron population created via thermo-ionic emission of an incandescent filament. The first LINAC was 4.5 m in length, providing 48 nC (3×10^{11} electrons) in 20 ns [6]. After the interaction with a high-Z solid target, the resulting positron population was accelerated by a second 4.5 m-long LINAC up to an energy of the order of 0.5 GeV [6]. The positrons were then stored and subsequently injected in the proton synchrotron (accelerated to 3.5 GeV), then the super proton synchrotron (accelerated to 20 GeV), and, finally, to LEP (>50 GeV). At the end of injection, the positron beam typically contained 14.7×10^8 particles in a transverse size of the order of 1 mm and a duration of the order of 20 ns. The obtained normalised emittance of the positron beam at 0.5 GeV was measured to be 60π mm mrad [7].

The quality of particle beams that can be obtained with this class of accelerators is still undisputed, but alternative more compact plasma-based methods are starting to emerge, with potentially appealing characteristics. Electron beams with energies of the order of the GeV are now routinely produced in moderate-size high-intensity laser laboratories (see, for instance, [9]), with the current record set at around 4 GeV [10]. The short duration of these electron bunches (as short as a few fs), combined with an overall charge in the range of 10 s to 100 s of pC, allows for unprecedented beam currents of the order of tens of kA. Without post-acceleration or beam transport, these electron beams naturally present divergences of the order of a few mrad [11] and a source size of the order of a few microns [12], implying a geometrical emittance of the order of a few mm mrad [13]. Recently, there is growing interest in producing hybrid machines that can in principle combine the compactness of a plasma-based accelerator with the high performance of a radio-frequency accelerator. Among other impressive results in this area, energy-doubling (from 21 to 42 GeV) has been recently reported for a positron beam propagating through a 1 m-long plasma accelerator [14].

Such laser-driven electron beams have recently been successfully applied to the generation of short and ultra-relativistic positron bunches, following pioneering work by Gahn *et al* [15]. Positron beams with energies of the order of hundreds of MeV have been generated with a duration of the order of tens of fs, divergence of the order of tens of mrad, and a source size of the order of 200–300 microns [4]. Interestingly, a similar experimental setup also allows for the generation of quasi-neutral electron–positron beams [5], an achievement with potential interest for laboratory astrophysics that has not yet

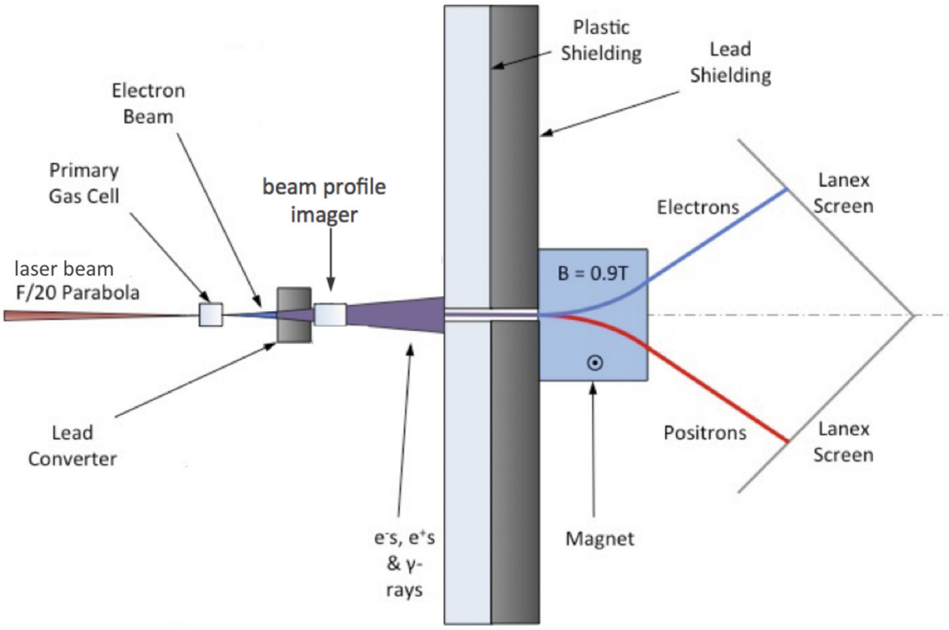

Figure 2. Sketch of the experimental setup.

been reached using more conventional radio-frequency accelerators. It must be noted here that alternative laser-driven methods based on direct laser irradiation of a solid target have also been reported in [16, 17], with the latter remarkably achieving quasi-neutrality in some shots. Despite the unquestionable interest of these results for potential laboratory astrophysics experiments [18], these methods rely on high-energy laser facilities and the comparatively broad divergence and low energy of the positron beam obtained make it difficult to use them as injection stages for high quality accelerators.

Here we report on recent experimental results devoted to characterizing laser-driven positron beams, in an experimental setup similar to that used in [4], especially addressing the possibility of using a laser-driven system as a preliminary injection scheme for hybrid particle accelerators. The structure of the paper is as follows: in section 2, the experimental setup will be discussed, whereas section 3 will show the main results of the campaign. Section 4 will then compare these results with the requirements for injectors in positron accelerators showing how a laser-driven setup is a realistic alternative to more conventional, radio-frequency approaches. Concluding remarks will then be given in section 5.

2. Experimental setup

A top-view sketch of the experimental setup is shown in figure 2. The experiment was conducted using one of the two twin beams of the Astra-Gemini laser facility [19], hosted by the Rutherford Appleton Laboratory UK. The laser beam had a duration of 43 ± 2 fs (full width half maximum, FWHM) and contained approximately 14 J after compression in an unfocussed beam diameter of 15 cm. In order to ensure more stable electron acceleration, the laser beam was apodised to a diameter of 12 cm, reducing the laser energy down to 9 J. This beam was focussed by an off-axis parabola with a 3 m focal length down to an oblate focal spot of FWHM (27 ± 3) μm $\times(31 \pm 4)$ μm containing approximately 40% of the laser energy (laser intensity of 6×10^{18} Wcm^{-2} corresponding to a dimensionless intensity $a_0 \approx 2$). The focus of the laser was positioned 0.5 mm inside a 10 mm long gas-cell filled with a mixture of 3% Nitrogen and 97% Helium at a backing pressure of 500 mbar. Optical interferometric data indicate that, once fully ionized, this pressure corresponds to an electron density of 4×10^{18} cm^{-3}. The temporal phase of the laser beam was controlled using a DAZZLER, in order to optimize the electron acceleration process that, for our parameters, operates in a regime of ionization injection [20]. Typical electron spectra obtained in this setup are shown in figure 3.

The electron spectra show a broad distribution with a maximum energy of the order of 500 MeV and a number of electrons exceeding 40 MeV (minimum energy detectable by the spectrometer, see below) of the order of 4×10^8 (corresponding beam charge of 60 pC). Independent measurements of the electron beam source size, inferred from betatron measurements, indicate it to be of the order of 1–2 μm for very similar experimental conditions [12], whereas, in a continuous injection scheme, the temporal duration of the electron beam can be estimated as $\tau_{e^-} \approx r_b/c$, where r_b is the radius of the accelerating bubble in the plasma [21]. For our experimental parameters, $\tau_{e^-} \approx 30$ fs, resulting on a beam current of the order of the kA. It must be noted that this is larger than what reported in [22], where the fs-scale duration of the electron beam is attained thanks to being only slightly above the threshold for ionisation injection. On the other hand, the divergence of the electron beam is measured to have a FWHM of (3.0 ± 0.2) mrad. A lead converter of variable thickness (ranging from 5 mm to 4 cm) was inserterd after the gas-cell, in a setup similar to what described in [4, 5]. A LANEX scintillator screen [23] was positioned 2 cm downstream of the lead converter, in order to measure the spatial distribution of the electrons and positrons escaping the rear surface of the converter. Even though the LANEX

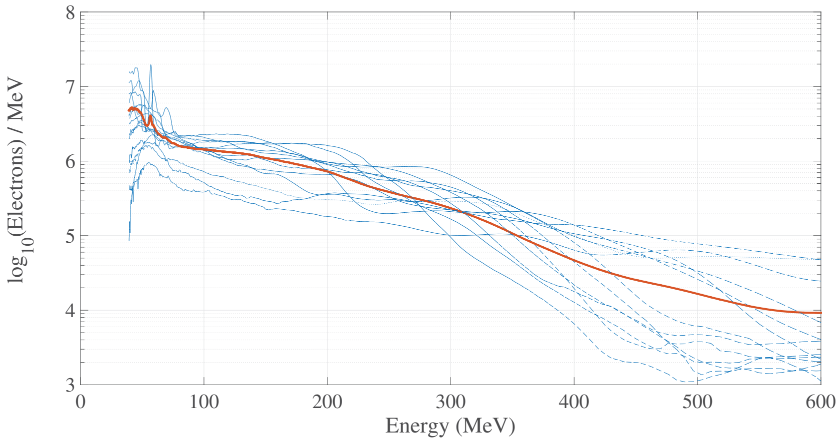

Figure 3. Typical electron spectra arising from laser wakefield acceleration in the gas-cell. Dashed blue lines indicate single-shot spectra, whereas the brown line represents an average.

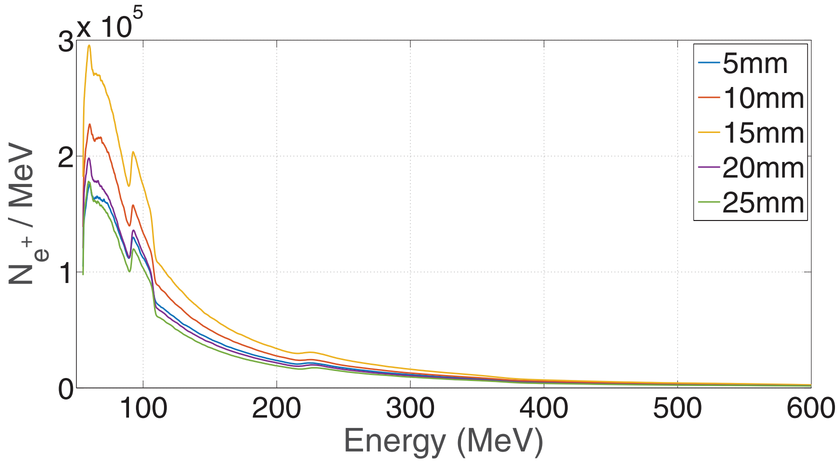

Figure 4. Average positron spectra experimentally measured for different target thicknesses, as indicated in the legend. The spectra for each target thickness have a shot-to-shot fluctuation of the order of 30%.

screen is effectively not able to distinguish between multi-MeV electrons, positrons, and gamma-ray photons, Monte-Carlo simulations using the code FLUKA [24] were carried out in order to discern the contributions of these three species on the detected signal. A magnetic spectrometer consisting of a 0.9 T, 10 cm long dipole magnet and a pair of LANEX screen were then placed in order to simultaneously extract the electron and positron spectra at each shot. Due to the arrangement of spectrometer, the minimum particle energy detectable is of the order of 40 MeV. The signal on the LANEX screen was absolutely cross-calibrated using imaging plates [25].

3. Experimental results

Typical positron spectra obtained for different thicknesses of the converter target are shown in figure 4. All spectra show a monotonically decreasing shape with a maximum energy of the order of 400 MeV and a clear relation between the converter thickness and number of particles. The maximum positron yield is obtained for a converter thickness of the order of 2–3 radiation lengths (see figure 5).

This result, in agreement with previously published results in similar conditions, is understood if we consider that a radiation length can be intuitively interpreted as the length over which a single step in the cascade has the maximum probability to occur. A distance shorter than two radiation lengths does not allow for the positron generation to be maximized, whereas a distance longer than two radiation lengths induces the newly generated positrons to lose energy via bremsstrahlung and effectively seed the cascade again.

By integrating the spectra reported in figure 4, it is possible to extract the average number of positrons with energy exceeding 40 MeV for each converter thickness. These results are shown in figure 5. A maximum measured positron yield (positron energy more than 40 MeV) of $(2.5 \pm 0.7) \times 10^7$ is measured for a target thickness of 15 mm ($\approx 2.6\ L_{\mathrm{RAD}}$). Assuming a Maxwell–Jüttner distribution for all positron spectra, this implies a number of relativistic positrons (positron energy exceeding 1 MeV) of the order of 10^9, in agreement with results reported in [5].

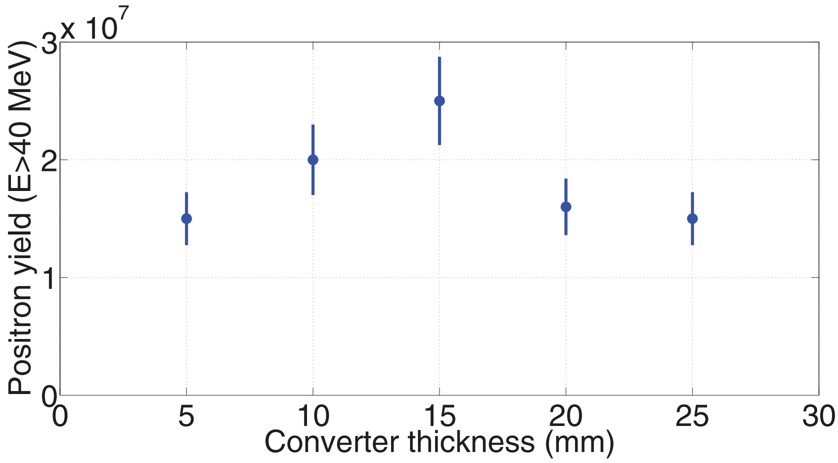

Figure 5. Experimentally measured number of positrons with energy exceeding 40 MeV escaping the converter target. Error bars represent shot-to-shot fluctuations.

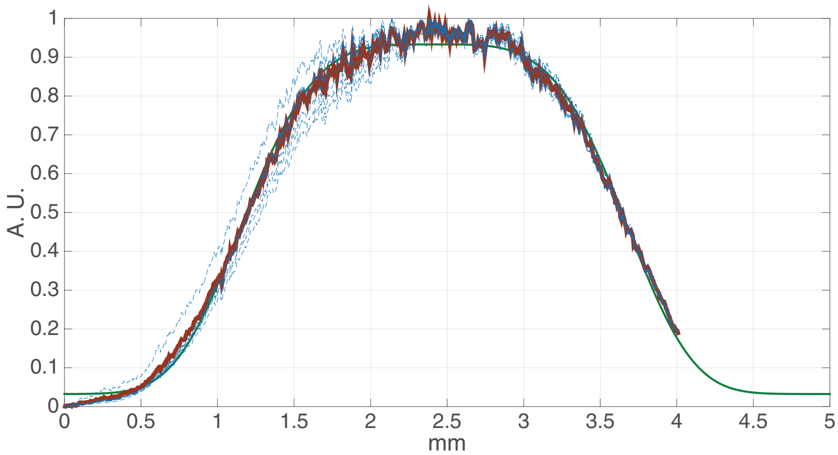

Figure 6. Lineouts on the beam profile imager placed 2 cm away from the rear surface of the converter target. Dashed blue lines: single shot line-out with the brown thick line representing their average. Green solid line: super-gaussian fit ($R^2 = 0.995$).

On the other hand, typical signal from the beam profile imaging for a converter thickness of 15 mm is shown in figure 6. The spatial distribution is remarkably stable on a shot-to-shot basis and well-approximated by a super-gaussian distribution with a FWHM of 2.4 mm (shot-to-shot uncertainty of 3%). Monte-Carlo simulations using the code FLUKA indicate a beam source size at the exit of the converter of 200 ± 50 μm, implying an overall beam divergence of ≈ 100 mrad. Assuming that the divergence of the electromagnetic cascade is $\theta_{\text{CAS}} \propto \sqrt{(d/L_{\text{RAD}})}/\gamma_e^+$ [26], with d the converter thickness and γ_e^+ the positron Lorentz factor, this divergence is consistent with $\gamma_e^+ \approx 17$, which is the average Lorentz factor of the positron distribution, in agreement with results reported in [5, 26]. As a caveat to this interpretation, it must be noted that it is hard to separate the contribution of the positrons from the electrons and photons to the signal on the image profile, since photons are expected to significantly outnumber the charged particles escaping the rear side of the converter [27]. However, the photon and positron beams can be assumed to have similar divergence, as corroborated by FLUKA simulations, suggesting that the present estimate of the positron divergence and average Lorentz factor is qualitatively correct.

4. Discussion

Calculations of the interaction of the primary electron beam with the converter target indicate a temporal spreading induced by the cascade of 5–10 fs, depending on the final positron energy. Assuming a duration of the primary electron beam to be of the order of 30 fs, we can then assume the positron population escaping the converter target to have a temporal duration of ≈ 40 fs. For the case of maximum positron yield (converter thickness of 15 mm), this translates into a positron current of the order of 0.4 kA.

In order to check whether it is possible to implement such a laser-driven positron generator as an injector for large-scale positron accelerators, it is necessary to compare the emittance of the beams generated in the present experiment with that of typical injectors of conventional accelerators. The injector stage of the LEP described in the introduction produced a positron beam that, before entering the proton synchrotron, has an energy of the order of 500 MeV. Before the positron-accelerating LINAC, the positron beam has an energy of 90 MeV (energy spread of $\pm 7\%$), a half beam size of 10.5 mm and a half beam divergence of 6 mrad [28]. These values result in a geometrical emittance of 62 π mm mrad. After the positron-accelerating LINAC the geometrical emittance was of the order of 0.1 π mrad mm and 0.03 π mrad mm in the two transverse dimensions, respectively [7]. These values are not dissimilar from that obtained in the present experiment. Assuming an energy slice of 90 MeV $\pm 7\%$ to be selected in the positron spectrum (using, for instance, a magnetic chicane), we obtain a full source size of 200 ± 50 μm and a full divergence of 25 ± 5 mrad. With these values, the geometrical emittance of the positron beam around 90 MeV can be estimated from our experiment to be (1.7 ± 0.5) π mm mrad. On the other hand, the geometrical emittance at 500 MeV of the positron beam generated in the present experiment can be estimated to be ≈ 0.3 π mm mrad. These emittances are then tolerable in large-scale accelerators, effectively suggesting that the spatial quality of the positrons generated in a laser-driven configuration could be used as a seed for hybrid (i.e. laser-plasma/conventional) positron accelerators.

However, there are a couple of major differences in the two configurations (laser-driven versus radio-frequency accelerators) that must be taken into account. First of all, the present status of laser-driven electron acceleration allows for the generation of ultra-relativistic electron beams with a maximum overall charge in the range of a few nanoCoulomb. It must be noted here that the spectral shape of the electron beam is virtually irrelevant for positron generation, since the quantum cascade introduces a spectral spreading close to 100%, regardless of the spectral shape of the primary electron beam. In this sense, it is thus preferable to have high-charge and broad-spectrum electron beams. In this situation, the number of relativistic positrons that can be effectively produced would be of the order of 10^9–10^{10}, at least one order of magnitude lower than what can be produced in the injection stages of large electron–positron colliders ($>10^{11}$. On the other hand, the remarkably short duration of primary electron beams generated by the laser wakefield, implies that extremely high positron currents can be generated, with realistic values in the range of a kA (compare it with typical positron currents of a fraction of an A in conventional accelerators [29]).

Another potential limitation of laser-driven positron beams is the repetition rate at which they can be generated. Current high intensity laser systems normally operate at a repetition rate of a fraction of a Hz, i.e. much slower than conventional accelerators (LEP operated at a maximum repetition rate exceeding 10 kHz). The possibility of improving the repetition rate of high-intensity laser, and thus achieving higher average-power systems is currently an active area of research with, for instance, realistic plans to produce a 10–100 Hz repetition rate high-intensity lasers (see, for instance, the DiPOLE project [30]).

The combined effect of a relatively low number of particles generated and a low repetition rate of laser-driven system is presently limiting the maximum luminosity achievable by these beams in a hypothetical laser-driven electron–positron collider. For the sake of this discussion the luminosity can be defined as:

$$L = \frac{n_b f N_{e^-} N_{e^+}}{4\pi\sigma_x\sigma_y}, \tag{2}$$

where N_{e^-} and N_{e^+} are the number of electrons and positrons in the beams, n_b is the number of bunches in each beam that circulate at a frequency f (1 for current laser-driven systems but up to 8 for LEP), and σ_x, σ_y the transverse dimensions of the beams. Current laser-driven technology can realistically provide counter-propagating electron and positron beams with a number of particles of the order of 10^9, respectively, and a transverse size of the order of 200 μm. Assuming a laser operation at approximately 1 Hz, a luminosity of the order of $L_{\mathrm{LASER}} \approx 10^{20}$ cm^{-2} s^{-1} can be attained. It must be noted that this is remarkably smaller than a reported maximum luminosity obtained in LEP of the order of $L_{\mathrm{LEP}} \approx 10^{31}$ cm^{-2} s^{-1} [31].

However, there are routes that are currently explored in order to significantly improve the performance of these laser-driven machines. For instance, there is a world-wide dedicated effort to increase the average power of high intensity lasers, in order to bring them up to kW range. Realistic projects are currently underway to generate 100 Hz systems, with 10 Hz already operational (see, for instance, [30]). Moreover, due to the good degree of laminarity of the electron–positron populations generated during a few-step electromagnetic cascade [3], a reported physical source size of the positrons of the order of 200 μm [5] is likely to correspond to a much smaller virtual source size, implying that one can envisage focussing systems able to generate transverse source sizes in the range of tens of microns. Finally, it must be considered that the spectral shape and the angular distribution of the laser-wakefield accelerated electrons are not strictly relevant in optimising the positrons generated during the cascade. It is thus preferable to devise laser-wakefield acceleration schemes that maximise charge and maximum energy in the electron beam. With appropriate bubble loading [32], one can realistically assume a few nC electron beams, resulting in 10^{10}–10^{11} particles. With these parameters, that are potentially achievable in the future, one can realistically expect to work in the direction of achieving a luminosity, for a laser-driven electron–positron collider, of the order of $L_{\mathrm{LASER}} \leqslant 10^{28}$ cm^{-2} s^{-1}, of interest for meaningful colliding experiments.

As a final remark, it must be noted that an international project is currently underway to produce the next generation of electron–positron colliders based on radio-frequency technology. The international linear collider (see technical design reports in [33]) is proposed to be a 37.5 km long machine, with planned centre-of-mass energy ranging from 200 to 500 GeV. Due to its design, the machine will be unlikely to optimally function for centre-of-mass energy below 150 GeV. Nonetheless, smaller-scale electron–positron colliders with centre-of-mass energies in the range of 1–10 GeV are still of interest for fundamental physics studies since they will allow, for instance, studying the hadronic contributions to the muon anomalous magnetic moment [34], hadronic contributions to the fine structure constant [35], spectroscopy, and photon-photon cross-section [36], justifying the world-wide effort in particle acceleration towards the generation of small-scale electron–positron colliders with a centre-of-mass energy in the range of 1–10 GeV.

5. Conclusion

In conclusion, we report on experimental results focussed on spatially and spectrally characterising ultra-relativistic positron beams generated in a fully laser-driven setup. Using a relatively small laser system, it is possible to generate positron beams with unprecedented current and remarkably low emittance, which would be acceptable for injection in a conventional radio-frequency accelerator. However, the relatively low average power of currently available laser systems is still the major limitation in implementing this technique for meaningful particle physics experiments, with current studies focussed on addressing this issue.

Acknowledgments

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